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FREDERICK A. MILAN

Department of Physiology
Arctic Aeromedical Laboratory

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ABSTRACT

Five experiments which investigated thermal balance in two clothed men in the cold were carried out at Little America V in the winter months of June and August. Environmental temperatures ranged between -32° and -47° C, and wind velocities ranged between 2 and 17 miles per hour during the experiments. Despite the protective clothing worn and the heat productions of between 3 and 4.8 mets (measured by indirect calorimetry), total heat debt (obtained by measurements of rectal and skin temperatures) ranged between 105 and 126 kilocalories for exposures of 40 to 165 minutes in duration. Finger temperatures ranged between 7° and 18° C at the end of the experiments. The thermal demand of the environment on these seemingly adequately clothed men was high, and it is suggested that they were moderately cold stressed despite high rectal temperatures.

THERMAL STRESS IN THE ANTARCTIC *

It is of some interest to know the amount of physiological strain acceptable to a clothed man in a cold environment. During the course of a year at Little America V in the Antarctic, the maintenance of thermal balance in heavily clothed men engaged in various activities in the cold was investigated. These experiments were undertaken to assess the efficacy of the protection provided by the winter clothing, to quantify the amount of cold exposure experienced by the expedition personnel, and to measure the intensity of environmental stress.

A number of studies of the thermal exchange between clothed men and a cold environment have been concerned with the effects of light clothing worn while engaged in moderate activity or while resting (Gagge, et al., 1941). In contrast, Belding, et al. (1947), studied two men who were dressed in a standard Arctic Uniform and were exposed in a cold chamber to a temperature of -17.7° C. Their activities were varied in order to involve a wide range of energy production. Energy losses exactly equaled energy productions at a metabolic level of about 250 kcal/hr/M^2. Below approximately 200 kcal/hr/M^2, changes in energy loss by the combination of convection and radiation were most important, whereas at higher energy production levels, sweating and external work were the most important. The resistance provided by the clothing against heat losses by convection and radiation (i. e., the clo value) was more than twice as great when the subject sat or stood quietly than when walking moderately fast. It was shown that increased convective losses were not caused by actual infiltration of cold air into the clothing at the garment openings or through the outer wind shell, but were a result of mixing the air trapped under the wind shell garments. On the basis of these data on the insulation provided at various activities, these authors provided a predictive graph for prolonged comfort at various temperatures.

In a separate paper, Belding, et al. (1947) reported the average effects of walking up a 6.5 percent grade at 3.5 mph in an Arctic Uniform at three environmental temperatures. During a 2-hour exposure at -40° C, an energy expenditure of 317 kcal/hr/M^2 was sufficient to maintain comfort. During the same activity, the subject felt warm at -29° C and hot at -17.7° C.

Carlson, et al. (1949) utilized an experimental thermal gradient suit to investigate performance and energy balances under various cold stresses.

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The insulative value of this suit was approximately 7.0. These experiments were undertaken at temperatures ranging between -40.5° and -23.5° C. There was no wind. Walking at 2 mph at the lower temperatures was sufficient to restore heat balance. Walking at 4 mph resulted in excess heat.

Adam (1948), using the knitted wire suit devised by Wolff (1958), has contrasted subclothing temperatures in antarctic sojourners with their subjective sensations of heat and cold. He concluded that these cold-acclimatized persons were not comfortable at skin temperatures which are lower than those comfortable for unacclimatized subjects, but he did not report the skin temperatures which were measured.

Recently, Japanese investigators (Nei, et al., 1956) have described experiments undertaken in a cold room to test the thermal insulating efficiency of cold weather clothing. Subjects were exposed for 35 minutes to -40° C with air movement of 10 m/sec. The authors discovered that variations of body surface temperatures were dependent on differences in the individuals tested, as well as upon the type of clothing worn.

METHODS

Several of these experiments were performed in June; the rest were undertaken in August 1957. The subjects were two civilian scientists who had been in the Antarctic at Little America V since the previous January. Their physical characteristics are shown in Table I.

TABLE I

WEIGHT, HEIGHT, AND SURFACE AREA OF THE TWO SUBJECTS

Subject	Ht. cm	Wt. kg	*SA (M^2)
R. C.	183	73.6	1.92
P. C. D.	179	74.0	1.92

*SA calculated from nomogram based on the Dubois-Meek formula.

As the subjects had been in the Antarctic for more than 6 months, they had developed clothing assemblies which apparently satisfied them, and these were worn for the studies. By and large, the protective clothing assemblies were those worn every day and consisted of items of the standard Arctic Uniform issued by the U. S. Army Quartermaster Corps, and selected items of civilian apparel (Appendix).

Earlier workers have described clothing test methods (Newburgh and Harris, 1945). Carlson and Buettner (1957) have recently discussed the major considerations in the evaluation of environmental stress. They emphasize that below temperatures of 21° C, a statement of environmental stress should include: air temperature, wind decrement, and radiation increment. In the studies made in the Antarctic, it was not possible to measure radiation temperatures during these tests. In most cases, the sun was at a low angle on the horizon. Depending upon cloud cover, the sky probably acted as a "cold sink" as shown by the work of Hardy and Stoll (1954).

Skin temperatures under the clothing were read on a portable Yellow Springs Telethermometer. Insertion type thermistors were attached to the skin of the subject by a piece of plastic tape at the following locations: forehead, lateral upper arm, over scapula, chest, abdomen, lateral thigh, lateral lower leg, dorsum of the hand, dorsum of the foot, and index finger. Another thermistor was inserted 10 cm into the rectum and secured by tape.

Metabolic rates were determined by indirect calorimetry. The subject wore a nose clamp and breathed through a mouthpiece and an insulated rubber hose. Inspired air was drawn through an insulated rubber hose from under the clothing. Expired air volumes were determined on the respiration gasuhr developed by the Max Planck Institute (Müller and Franz, 1952). The instrument fitted into a caribou skin cover and was warmed by chemical heating pads. Gas volumes at BTPS were reduced to STPD by a nomogram. Aliquot samples, which were 3 percent of the total volume of expired air, were collected in punching bag bladders, and the gas samples were analyzed for oxygen content on a Haldane-Guthrie gas analyzer. Metabolic rates were expressed as kilocalories per hour per square meter of body surface by the product of the minute volume times a calorific value for the oxygen in expired air after the method of Weir (1949). During these measurements, freezing of spittle and water vapor in the plastic valve in the expired air circuit invalidated a number of metabolic runs.

An average skin temperature was calculated by multiplying temperature measurements at the various locations on the body by a weighting factor

TABLE II

RESULTS OF STUDIES IN THERMAL BALANCE SHOWING INITIAL AND FINAL RECTAL, AVERAGE SKIN, FOOT, AND FINGER TEMPERATURES AND TOTAL HEAT DEBT INCURRED

Dry Bulb Temp 0° C	Wind mph	Expo-sure mins	Tr^1	Tr^2	Ts^1	Ts^2	$T\ foot^1$	$T\ foot^2$	$T\ fing^1$	$T\ fing^2$	Total Heat Loss Kcal	Heat Production Mets
-36	17	44	37.5	38.5	32.5	26.0	25.0	18.0	33.5	7.0	105	3.0
-32	3	76	37.5	38.5	32.8	26.0	26.5	22.0	21.8	8.0	125	3.1
-31	2	75	37.1	37.4	32.0	27.2	23.0	17.0	25.0	10.0	122	3.1
-47	15	143	37.5	37.8	32.1	28.2	35.0	17.0	32.0	18.0	126	4.8
-39	8	165	37.0	38.6	32.9	26.0	29.0	34.0	30.0	16.0	109	4.4

determined by the surface area of the body involved in the measurement after Hardy and DuBois (1938). These factors are: average trunk (chest, abdomen, and scapula) X 0. 35, upper lateral thigh X 0. 19, lower lateral leg X 0. 13, dorsum of the foot X 0. 07, hand X 0. 05, upper lateral arm X 0. 14, and forehead X 0. 07. Mean body temperatures, the sum of 0. 6 times the rectal temperature and 0. 4 times the average skin temperature, were calculated. Heat lost from body storage was calculated by the serial product of the change in mean body temperature times the assumed specific heat of the tissues (0. 83) times the body weight in kilograms. This was expressed as heat debt in kcal/M^2. An average heat production was estimated by the product of the time spent in any one activity multiplied by the measured metabolic cost of that activity.

RESULTS

The results of five experiments are presented in Table II. Energy costs of some activities are shown in Table III. A "typical" experiment is illustrated graphically in Figure 1.

Shortly after the subject went outside, skin temperatures fell and rectal temperatures rose concomitantly. The rise in rectal temperatures was presumably due to the constriction of the superficial vasculature in response to the cold air stimulus, as well as the high levels of activity. The fall in skin temperature was a form of insulative cooling. During bouts of vigorous activity, it was noted that the rectal temperature was lowered as the skin surface temperature warmed. "Steady state" conditions were never achieved in these experiments, since falling skin temperatures were functions of exposure time.

In several instances during different experiments, the exposed skin on the tip of the nose and over the malars of the face was frozen, although the subject was actively perspiring and was subjectively hot.

Although body cooling increased with time of exposure and depended upon the cooling power of the environment, tolerance times at these temperatures were determined by the temperatures of the fingers, feet, and exposed face, as well as by the total body heat debt. The clothing assemblies worn daily in

TABLE III

ENERGY EXPENDITURE IN THE ANTARCTIC

Subject: F. A. M., Age 33, Wt. 70 kg, SA 1.78 M^2

Activity	Kcal/hr/M^2	Kcal/min
Walking, moderate pace, hard snow surface	147.5	4.4
Walking, moderate pace, 6" new snow	192.7	5.7
Walking, up 10% grade, hard snow, moderate pace	165.0	4.9
Walking, down 10% grade, hard snow, moderate pace	163.8	4.8

Subject: P. C. D., Age 33, Wt. 75 kg, SA 1.94 M^2

Activity	Kcal/hr/M^2	Kcal/min
Standing in cold	87.4	2.8
Standing in cold	85.8	2.8
Walking slowly, hard packed snow	150.9	4.9
Walking, brisk pace, up 10% grade	213.2	6.3
	244.9	7.9

Subject: R. C., Age 19, Wt. 73.6 kg, SA 1.92 M^2

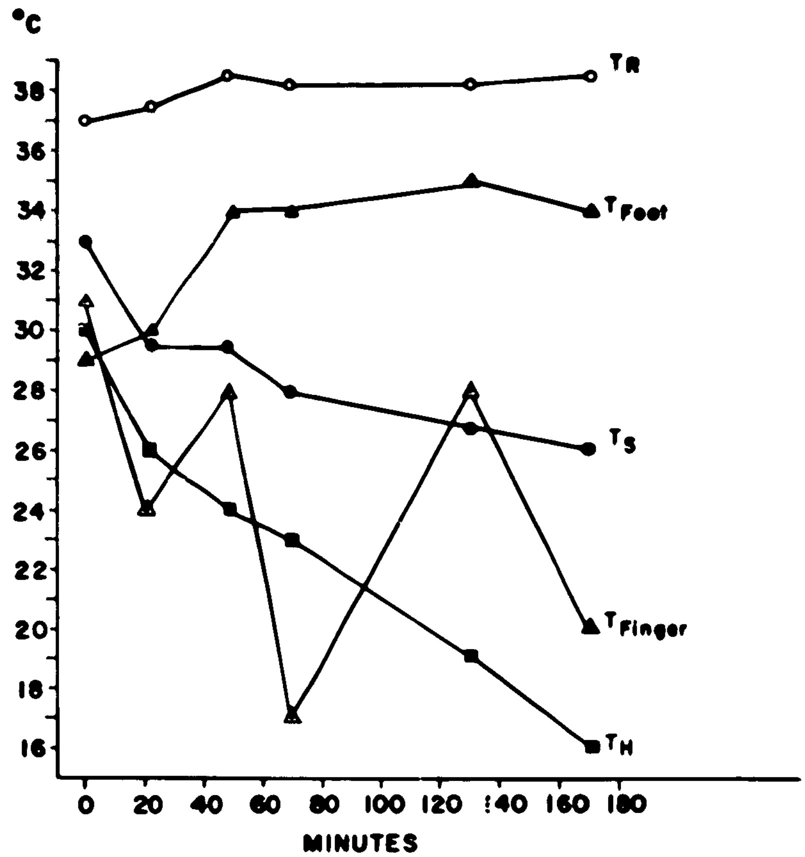
Activity	Kcal/hr/M^2	Kcal/min
Walking, level terrain, hard packed snow, stopping occasionally	129.7	4.1
	119.8	3.8
	93.8	3.0
Walking, level terrain, hard packed snow, stopping occasionally	110.7	3.5
	153.7	4.9

TABLE III (Contd)

ENERGY EXPENDITURE IN THE ANTARCTIC

Subject: R. C., Age 19, Wt. 73.6 kg, SA 1.92 M^2 (Contd)

Activity	Kcal/hr/M^2	Kcal/min
Walking, slow pace, subject warm	130.3	4.2
	130.2	4.2
Walking, up 10% grade, brisk pace	192.0	6.1
Walking, up 10% grade, brisk pace	218.2	7.0



RECTAL ○, AVERAGE SKIN ●, FOOT ▲, HAND ■ AND FINGER △ TEMPERATURES OF SUBJECT R.C. AMBIENT AIR TEMPERATURE -39 °C, WIND 8 MPH DURING THE EXPERIMENT. THE SUBJECT WALKED FOR 6 MILES AT A MODERATE PACE ON HARD WIND PACKED SNOW. HEAT PRODUCTION AVERAGED 220 Kcal/hr/m^2.

Figure 1.

the Little America V camp area would not be suitable for extended trips at these low temperatures without shelter and rewarming facilities.

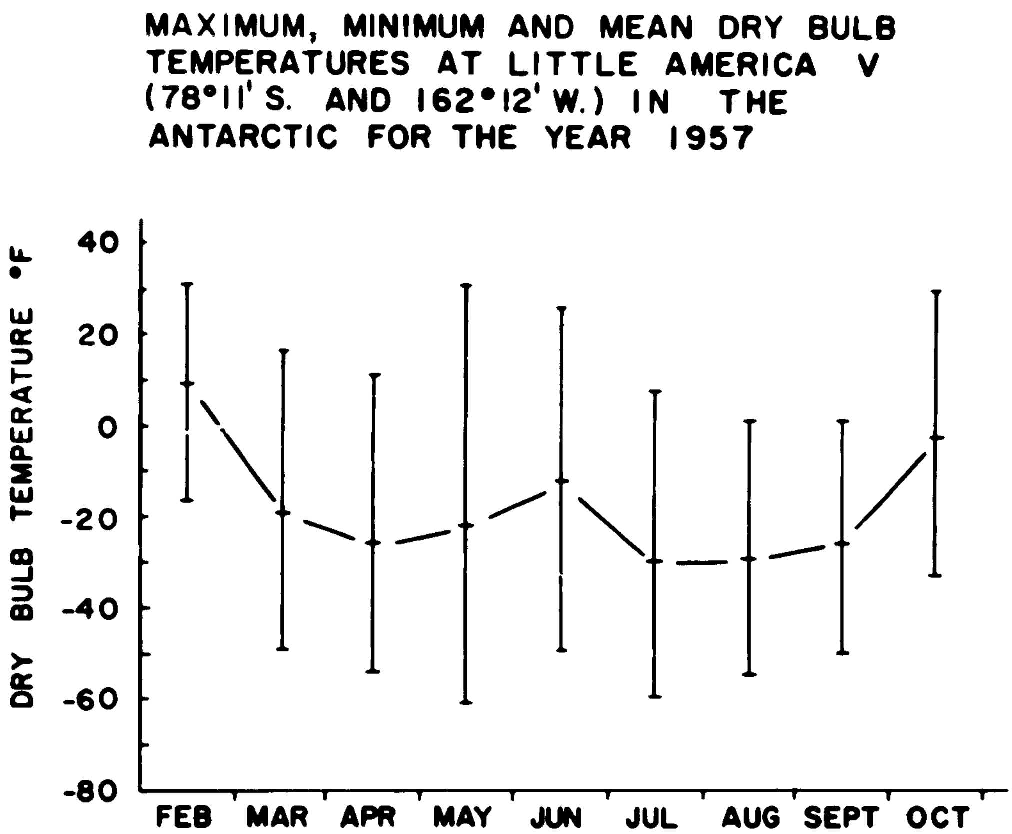
DISCUSSION

In experiments on the tolerance limits of clothed men in 0° C water, Hall and Polte (1955), based on the earlier work of Taylor (1945), accepted 90 kcal as an arbitrary limit for total body heat debt. Belding (1949) has stated that 40 to 90 kcal per square meter of body surface area, or approximately 80 to 160 kcal, may be removed from an initially warm man without undue discomfort. Hammel, et al. (1959) have reported that six central Australian Aborigines incurred an average heat debt of 84 kcal per square meter of body surface area while sleeping in an experimental cold box designed to simulate winter in central Australia. Sleep was compatible with this heat debt in the natives, but not in Caucasian controls. The diurnal fluctuation of rectal temperature is, of course, a complicating factor in the computations of heat debt in sleeping experiments.

The antarctic subjects incurred total heat debts ranging between 105 and 126 kcal, and they were subjectively cool and uncomfortable at times. It is suggested that these subjects were moderately cold stressed. The elevated rectal temperatures were a complicating factor in the calculations of heat debt.

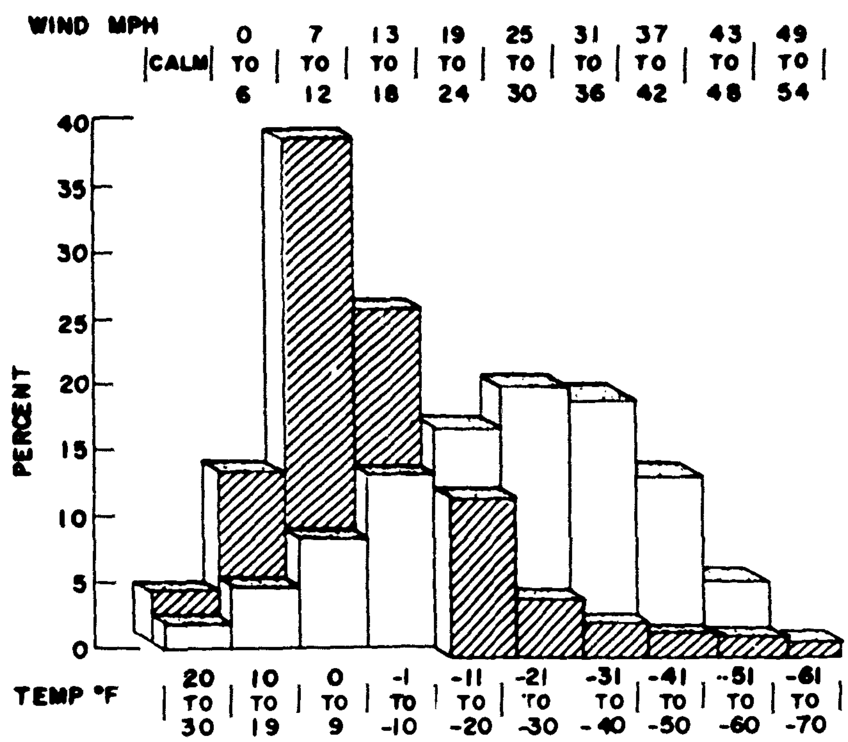
One should contrast skin and rectal temperatures measured in the antarctic subjects with measurements of the same parameters in similar studies of the Alaskan Eskimo (Milan, 1960). The Eskimo remained in thermal balance up to 8 hours at temperatures of -26° to -14° C with winds of 0 to 24 knots because of the greater insulation of their clothing.

The climate of the Little America region of the Antarctic provides meteorological conditions which are challenging to the most imaginative clothing designer. Figure 2 shows maximum, minimum, and mean dry bulb temperatures. Low temperatures and high wind frequently occur coincidentally. Figure 3 and Tables IV and V illustrate the frequencies of wind speeds and dry bulb temperatures during the period March-October 1957. Wind velocities in excess of 7 mph occurred for about 80 percent of the observations which were taken every 3 hours. Dry bulb air temperatures below



MAXIMUM, MINIMUM AND MEAN DRY BULB TEMPERATURES AT LITTLE AMERICA V (78°11' S. AND 162°12' W.) IN THE ANTARCTIC FOR THE YEAR 1957
DRY BULB TEMPERATURE °F
40
20
0
-20
-40
-60
-80
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEPT
OCT

Figure 2.



FREQUENCIES OF WIND VELOCITIES (HACHURE) AND DRY BULB TEMPERATURES MARCH TO OCTOBER 1957 LITTLE AMERICA V

Figure 3.

TABLE IV

NUMBER OF HOURS AND FREQUENCY OF WIND SPEEDS
IN MPH AT LITTLE AMERICA V IN 1957

Wind Speed	Calm	0-6	7-12	13-18	19-24	25-30	31-36	37-42	43-48	49-54
March	14	127	343	155	87	17				
April	41	139	346	125	33	10	6			
May	66	89	255	157	98	30	27	12	4	6
June	39	65	183	225	119	43	31	15		
July	22	114	253	231	86	35	2			
August	28	80	278	192	91	31	10	13	13	6
September	30	83	392	202	12	1				
October	19	74	211	229	123	45	28	12	3	
Total Hours	259	771	2261	1516	669	212	104	52	20	12
Percentage	4.4	13.1	38.4	25.7	11.3	3.6	1.7	0.8	0.3	0.3

TABLE V

NUMBER AND FREQUENCY OF OCCURRENCE OF DRY BULB TEMPERATURES AT LITTLE AMERICA V IN 1957

Temp °F	20 to 30	10 to 19	0 to 9	-1 to -10	-11 to -20	-21 to -30	-31 to -40	-41 to -50	-51 to -60	-61 to -70
March		12	50	213	228	162	71	8		
April			56	45	71	210	162	148	28	
May	37	35	82	97	49	84	120	116	116	8
June	16	110	103	108	86	165	104	26	2	
July			26	69	92	118	185	159	94	1
August			1	20	145	223	181	134	40	
September				38	150	133	235	159	5	
October	51	101	159	184	147	66	35	1		
Total	104	258	476	774	968	1161	1093	751	285	9
Percentage	1.7	4.4	8.1	13.1	16.4	19.7	18.5	12.8	4.8	0.1

-30° F (-34.5° C) were observed for 37 percent of the observations. It should be noted that fallen snow commences to drift at about 7 mph giving an added supercooling effect on exposed flesh. Given the types of clothing assemblies habitually worn by the expedition personnel who were studied, it was seen that the environmental conditions were sufficient to cause moderate thermal stress and consequent physiological strain.

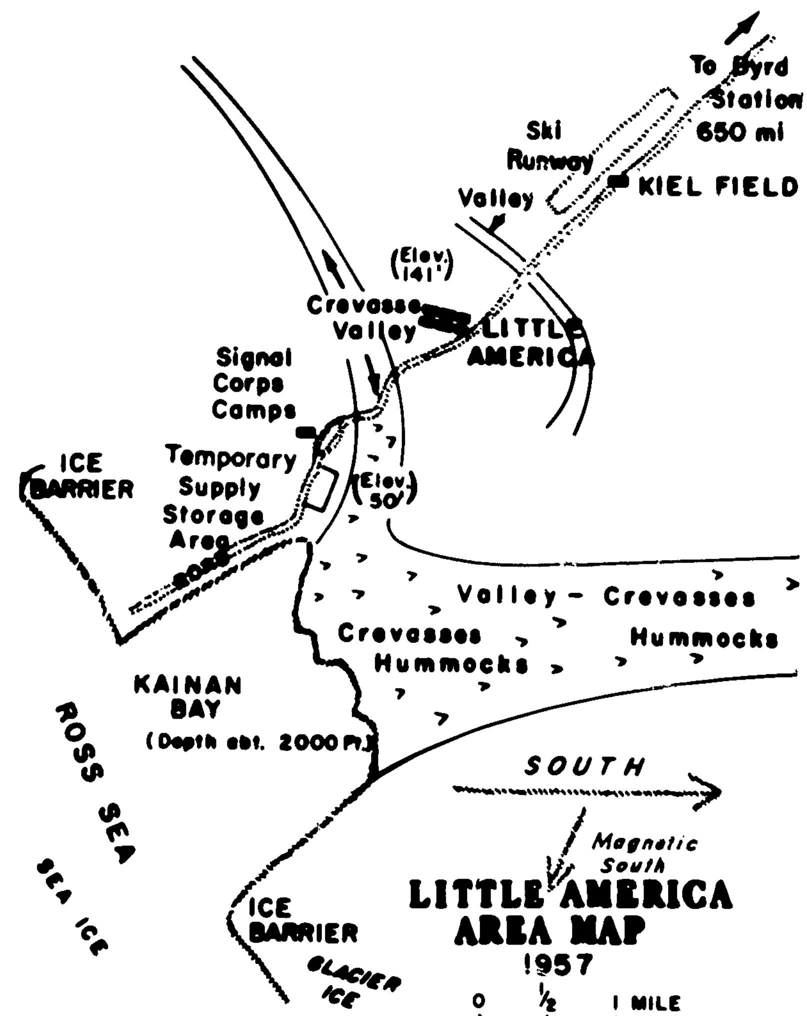

To Byrd Station 650 mi
Ski Runway
KIEL FIELD
Valley
(Elev. 141')
Crevasse Valley
LITTLE AMERICA
Signal Corps Camps
ICE BARRIER
Temporary Supply Storage Area
(Elev. 50')
Valley - Crevasses
Crevasses
Hummocks
Hummocks
KAINAN BAY
(Depth abt. 2000 Ft.)
ROSS SEA
SEA ICE
SOUTH
Magnetic South
LITTLE AMERICA AREA MAP
1957
0 ½ 1 MILE
ICE BARRIER
GLACIER ICE

Figure 4.

ACKNOWLEDGMENTS

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APPENDIX

Clothing: Assembly of P. C. D.

1. Jockey-type undershorts
2. 2-piece, long underwear, QMC
3. Wool shirt, 8 percent wool, 20 percent nylon, QMC
4. Wool sweater, hand knit, red
5. 1 pair cushion sole socks, QMC
6. 1 pair ski socks, QMC
7. Arctic felt boots, QMC
8. Pile cap, QMC
9. Wool glove inserts with fingers, QMC
10. Leather chopper mittens
11. Field jacket with liner and hood, QMC, (1951)
12. Field trousers with liner, QMC

Clothing: Assembly of R. C.

1. Jockey-type undershorts
2. 2-piece underwear, waffle weave, USN
3. Light weight khaki pants, USN
4. Wool shirt, QMC
5. Cushion sole socks, QMC
6. White thermal boots (combat boots), QMC
7. Field jacket with liner and hood, QMC (1951)
8. Arctic uniform pants with liner, QMC
9. Wool mitten insert, QMC
10. Over mitten, QMC
11. Wool Balaklava helmet

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